Briefing Paper

"Characterizing the Range of Children's Pollutant Exposure during School Bus Commutes"

Contract Number 00-322, October 2003

Abstract

This study of children's exposures while riding school buses was the most comprehensive study of its type ever conducted. Pollutant concentrations were measured on board buses of various ages and types, driven over actual bus routes in Los Angeles. The three factors with the greatest overall effect on bus cabin concentrations were (a) "self-pollution" from the bus's own emissions (b) emissions from other vehicles on the road as reflected by traffic density, and (c) ambient "background" concentrations in the vicinity of the roadways traveled.

The self-pollution effect was highest for older buses under closed window conditions, with diesel vehicle-related pollutant (DRP) concentrations up to 2.5 times higher than during open window conditions. During runs of different traffic density, DRP concentrations were two to three times higher on urban routes with dense traffic as compared to the same bus driving on rural/suburban routes with light traffic.

Accurate interpretation of the study results requires consideration of several caveats. The most important caveats are that both the number of buses studied and the number of runs conducted for each bus were small, and the variability in measured concentrations from bus to bus and from run to run was large.

To put the results into an exposure perspective, Air Resources Board (ARB) staff compared riding uncontrolled diesel school buses, at concentrations measured in this study, for school years K-12, two hours per school day, to concentrations measured in passenger cars in Los Angeles in a different ARB study. Lifetime diesel exhaust particulate matter (DPM) exposure and cancer risk due to DPM

increased by about 5%. This risk was estimated to be significantly less than the risk of death in an auto accident if the same travel was made in a passenger car. Although these two aspects of risk are not directly comparable, they indicate that there are considerable personal safety benefits associated with using buses rather than passenger cars to transport children to school. Nevertheless, this and previous studies provide compelling data that exposures occurring during commutes, whether on buses or in cars, are significantly elevated and need to be reduced.

Exposure reduction recommendations from this report include replacing older diesel school buses with natural gas-powered or particulate trap-equipped buses, assigning the newest and cleanest buses to the longest routes, and avoiding caravanning of buses through staggered departure times.

Introduction

Research has shown that concentrations of vehicle-related pollutants on and near roadways can be up to ten times higher than those measured at the nearest ambient monitor (e.g., Rodes et al., 1998; Lawryk et al., 1995; Chan et al., 1991; and Shikiya et al., 1989). Diesel vehicle-related pollutants such as DPM are of particular concern (Lloyd and Cackette, 2001). About 70% of California school buses are diesel-powered. Diesel exhaust has been associated with an increased allergic response to allergens (Diaz-Sanchez et al., 1994, 1996) and an increased risk of lung cancer (Bhatia et al., 1998; ARB, 1998).

To help determine if children's time spent on and near diesel-powered school buses leads to high exposures, the ARB sponsored a detailed study by University of California Los Angeles (UCLA) and University of California Riverside (UCR) researchers of pollutant concentrations inside and near school buses. Pollutant concentrations were measured inside and outside five uncontrolled diesel school buses driven along actual school bus routes in Los Angeles. For comparison, limited testing of a diesel bus outfitted with a particulate trap and a bus powered by natural gas was also conducted. Buses were outfitted with dual sets of real-time instruments, which allowed direct front versus back and inside versus outside comparisons. In addition, a tracer gas was added to each bus's own exhaust to help determine the bus's own contributions to on-board concentrations. The overall objective of this study was to characterize the range of exposures experienced by children during their school bus commutes, especially in potentially high exposure conditions. An associated objective of the project was to determine what factors most strongly influenced exposures.

Project Summary

The study was conducted from late April to early June, 2002. Students were not on board the buses during the tests. Actual bus routes were driven at the same time of day as the students' commute, with the same bus stop locations and times as the actual school bus routes. The primary urban route driven was about 18 miles each way, taking about 75 minutes to travel from bus stops in South Central Los Angeles to a magnet school in West Los Angeles in the morning, followed by the reverse in the afternoon. Traffic on this route was very heavy and included significant time on congested freeways. For comparison, some of the runs were made on a secondary urban route that used only surface streets, and on a third suburban/rural route with much lighter traffic. Twenty runs were made on the primary urban route, four on the second urban route, and seven on the suburban/rural route. Three additional runs were devoted to the effect of window position, and two additional runs measured concentrations at bus stops outside the bus.

Five diesel school buses, manufactured in 1975, 1985, 1985, 1993, and 1998 were used, along with a 1998 diesel bus outfitted with a particulate trap and a 2002 compressed natural gas-powered (CNG) bus. Buses were outfitted with a comprehensive array of measurement equipment with an emphasis on real-time measurements to be able to capture the rapidly changing concentrations typical of traffic. Dual sets of instruments were used to determine if significant concentration differences existed from front to back on the bus as well as differences inside versus outside the bus. Traffic and driving conditions were recorded by computer log and video to help analyze the effects of other vehicle emissions, traffic conditions, and driving conditions. Ambient concentrations and meteorological conditions recorded at nearby stationary locations were included in the analysis of effects.

To help differentiate the emissions from surrounding diesel vehicles from diesel emissions originating from the bus itself, an inert tracer gas, sulfur hexafluoride, was added to each bus's exhaust and measured on board. Sufficient concentrations were added so as to make the tracer detectable on all buses.

To simulate real-world conditions, test buses had closed windows in the morning runs and partially opened windows in the afternoon runs, as observed for that time of year in Los Angeles. The magnet school did not allow idling at the school, consistent with Los Angeles Unified School District policy at that time, and idling is now prohibited statewide.

Summary of Results

Pollution concentrations in vehicles are typically as high as roadway concentrations, due to high rates of air exchange in moving vehicles, even when windows are closed. Roadways usually have much higher concentrations of vehicle-related pollutants than ambient urban air. For example, a recent exposure assessment carried out by the ARB calculated that in-vehicle DPM concentrations average about five times higher than ambient concentrations, resulting in one-third of population DPM exposures occurring in vehicles, even though time in vehicles only amounts to about 6% of people's day (Fruin, 2003). Therefore, it is important to keep in mind that occupants of any vehicle in heavy traffic encounter high exposures to vehicle-related pollutants.

This study of school buses, however, demonstrated that diesel buses can have significantly higher on-board DRP concentrations than other vehicles, due to “self pollution,” or the intrusion of the bus’s own exhaust into the bus cabin after leaving the bus’s exhaust pipe. This effect appeared to be worse when windows were closed and worse for older buses. DRP concentrations were up to 2.5 times higher when windows were closed than when windows were open for a given diesel bus on a given route. These ratios matched the observation of the tracer gas concentrations being 2.6 times higher on average when windows were closed.

The influence of other traffic was also a key determinant of exposure. DRPs were two to three times higher on the congested primary urban route compared to the suburban/rural route for a given diesel bus at the same time of day with windows open. The two urban routes, one with a large portion of freeway driving and the other with only surface street travel, however, had similar concentrations.

The CNG-powered bus and the particle trap-equipped diesel bus, while also showing measurable self-pollution, showed significantly reduced on-board concentrations of DRPs compared to uncontrolled diesel buses. DRPs were two to five times higher on uncontrolled diesel buses as compared to the CNG or trap-equipped bus during closed window conditions. When windows were open, these differences were markedly reduced due to much higher ventilation rates. Pollutants related to natural gas combustion, such as formaldehyde, were higher on the CNG bus than other buses, so the relative differences shown by alternative fuels or control technology depended on the pollutant and were not necessarily always reductions. During the time of the study, a CNG-powered school bus with an oxidation catalyst was not available. Now, new CNG buses have catalysts to reduce formaldehyde emissions (Ayala et al., 2002).

For bus commutes of long length where idling at schools was not allowed, bus-related exposures were almost completely due to the commute itself and not the time spent at bus stops or loading and unloading.

The effect of seat position was modest, with somewhat higher DRP concentrations observed in the back of the bus when windows were closed, but these differences were small compared to other effects like window position or road type.

Interpretation of Results and Caveats

Accurate interpretation of the study results requires consideration of several caveats. The most important caveats are that both the number of buses studied and the number of runs conducted for each bus were small, and the variability in measured concentrations from bus to bus and from run to run was large. Like all vehicles, buses differ greatly in their emissions and performance. Emissions from the same bus also vary day-to-day, as seen in repeated dynamometer studies. Other factors such as meteorology and traffic conditions, which are not controllable in an in-vehicle exposure study, can also vary, although in this study they were relatively similar from day to day.

Although the study included buses of various ages and manufacturers, and a new natural gas and particle trap-equipped bus, it was not designed to provide generalized comparisons between various bus types or fuels. To be able to generalize the performance of buses by fuel type or control technology, direct measurements of the bus emission rates are needed, along with a large enough number of buses to be representative of a particular type of bus. These direct measurements are typically conducted using dynamometer laboratories that allow greater control of emissions-related variables and allow greater reproducibility, in part due to the use of pre-specified driving patterns.

This caution should be kept in mind when considering the relatively high DRP concentrations measured on the trap-equipped bus (as compared to the CNG bus). Trap technology has been demonstrated to be highly efficient in dynamometer studies, and it was expected that the DRP concentrations on the trap-equipped bus and on the CNG bus would be similar (Ayala et al., 2002). Because the performance of the particle trap was not directly measured, it is possible that the trap was not functioning at optimal efficiency during the study.

It should also be noted that windows were always closed in the mornings and always partially open in the afternoons, to simulate normal bus operating conditions. Vehicle-related pollutant concentrations tend to be higher in the morning in Los Angeles, due to lower wind speeds and lower mixing heights of the atmosphere as compared to afternoon conditions, and this may have contributed to the differences in on-board concentrations observed between open window and closed window conditions.

Lastly, it is important when evaluating some study results that the bus's own emissions sometimes affected the concentrations measured outside the bus (near the front of the bus). Therefore, outside-the-bus concentrations generally reflect roadway concentrations, but not always.

Exposure and Risk

This study found that exposures on uncontrolled diesel school buses, particularly when windows were closed, were significantly higher than on the trap-equipped bus or the CNG-powered bus in the same traffic conditions. To put these findings in perspective, ARB staff compared estimated exposures for various commute scenarios. Because passenger car travel is more dangerous than buses, the safety of the various modes of transportation was also considered. School buses are the safest vehicle (per passenger mile) to get to school, according to the Transportation Research Board (Transportation Research Board, 2002).

Exposure scenarios included commutes on the worst diesel bus, by average diesel bus, and by passenger car. It was assumed that a student rode a school bus during their entire K-12 education. Two, one-hour bus commutes per school day were assumed, with auto trips at 45 minutes each, assumed to be faster than buses. Black carbon measurements, converted to DPM, were used as a measure of cancer risk. Particulate matter less than 2.5 microns (PM2.5) was used as a measure of illness risk. The most significant illness risk was an increased risk of hospitalization due to asthma attack. Details of these calculations are given in Appendix A.

For cancer risk, the ARB assumed a student rode only uncontrolled diesel buses over all of their school years. This was compared to DPM exposures expected during car commutes, as calculated through a different ARB study, and the resulting difference in lifetime DPM exposure and cancer risk was about a 4% increase, or an increase of about 30 in a million lifetime risk.

This number should be considered highly uncertain because the cancer risk multiplier was developed from a range of plausible values and ambient DPM concentrations are also quite uncertain (there is no unique marker for DPM in ambient air). Nevertheless, it is useful to consider that these are small numbers compared to other dangers associated with vehicle travel. For example, the increased risk of crash fatality due to commuting by auto rather than bus appears to be higher than the increased risk of cancer due to commuting by uncontrolled diesel bus. Therefore, removal of a child from school buses because of cancer risk does not appear to be warranted from an overall safety and health standpoint. Rather, the recommendations listed in the following section for reducing exposure should be followed and/or advocated.

The PM2.5 calculations showed a 0.8% increased daily rate of asthma hospitalizations under worst-case bus conditions. The PM2.5 risk number is uncertain because it relied on the extremes of the range of PM2.5 concentrations measured in the bus study and much of the PM2.5 on buses did not come from the bus. In addition, the climate and pollution sources of the city where the asthma rate study was conducted, Seattle, was very different than Los Angeles. However, this number indicates that asthmatic children exposed to the worst-case diesel bus conditions may have additional cause for concern due to their sensitivity to particulate matter.

Recommendations

Based on the findings and recommendations of this report, the ARB recommends reducing children's school bus exposures to diesel exhaust through a combination of measures. It is important to accelerate the phasing in of natural gas-powered or particulate trap-equipped buses and the retirement of older, high-polluting buses. In the mean time, the newest and cleanest buses should be assigned to the longest routes; bus caravanning should be discouraged, such as through staggered departure times; and bus idling should be kept to a minimum (now CA law). Buses should be maintained diligently with one goal of preventing or minimizing visible emissions. In addition to avoiding following other buses, bus drivers should also be encouraged to avoid following closely behind diesel vehicles of any kind, especially those with visible emissions.

Children's time near arriving and departing buses should also be kept to a minimum, and where buses are not full, they should be encouraged to sit nearer the front of the bus, where concentrations are sometimes lower. For older and dirtier buses, windows should be kept open as often as rider comfort allows. However, on routes with heavy traffic, opening windows has the disadvantage of allowing higher peak concentrations from other vehicles.

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APPENDIX A
EXPOSURE CALCULATIONS FOR VARIOUS SCHOOL BUS SCENARIOS

Diesel Exhaust Particulate Matter

This section compares diesel exhaust particulate matter (DPM) exposures based on various school bus and passenger car commute scenarios, and compares the differences between these scenarios with overall DPM exposures. Scenarios included commuting by an average conventional diesel bus, a worst-case diesel bus, and a passenger car (PC) to represent the lowest on-road exposures.

Mean black carbon (BC) concentrations measured in the Children's Bus Study (Fitz et al., 2003) were used in the three bus scenarios, and the conversion factor between BC (µg/m³) and DPM (µg/m³) was assumed to be 2.04 (ARB, 1998). Passenger car BC concentrations were based on the results of Rodes et al., (1998) as calculated by Fruin (2003) for the year 2000.

Table 1. Average in-vehicle black carbon concentrations (µg/m³)

	Closed Windows (a.m.) (µg/m³)	Open Windows (p.m.) (µg/m³)	Average (µg/m³)
Conventional diesel bus avg[1]	12.5	5.9	9.2
Worst Bus[1]	19	9.1	14
Passenger Car[2]	5.9	na	5.9

(1) Children's School Bus Study (Fitz et al., 2003)
(2) Rodes et al. (1998), Fruin (2003); closed window conditions, Los Angeles

ASSUMPTIONS:
The average of morning and afternoon runs in the late spring and early summer adequately represented annual on-board BC averages in Los Angeles.

The five conventional diesel buses used in the study of Fitz et al. (2003) were reasonably representative of the bus fleet in Los Angeles.

A highly-exposed school child, if bused, took two, one-hour trips per day. The same child, if driven in a private car, took two, 45-minute trips per day, to cover equivalent distances.

The school year has 200 days. 13 school years were spent commuting, all with the same bus or type of bus.

Overall daily DPM exposure (expressed as BC) for children for Los Angeles was 1.1 µg/m³, as calculated from the California Population Indoor Exposure Model (CPIEM), for the year 2000, detailed in Fruin (2003). Ambient BC in Los Angeles was 1.2 µg/m³. Daily exposure was lower than ambient concentrations due to particle losses (deposition) in indoor environments.

CAVEATS

Passenger car measurements occurred five years earlier than the Bus Study measurements, when diesel vehicle fleet emissions were higher.

Two of the five conventional diesel buses were chosen specifically because of their visible emissions to represent high-emitting buses.

CALCULATIONS:

CHANGES TO DAILY BC EXPOSURE:

The changes to daily DPM exposure were calculated by taking the difference in average concentration between the transportation types, multiplying this by the time spent in transit, and then dividing by 24 hours to obtain the change in the 24-hour exposures. Because the PC trips were faster, the extra time in transport on buses was compared to ambient concentrations.

> Worst bus versus PC:
> (bus concentration minus car concentration for length of car trip) +
> (bus conc minus ambient conc for extra time of bus trip, 30 min) / 24 hrs =
> [(14 - 5.9) x 1.5 hrs + (14 – 1.2) x 0.5 hr] / 24=(12.2 + 6.4)/24=0.77 µg/m³
> added to daily average exposure of 1.1 µg/m³
> Percent increase = daily change / avg daily exposure = 0.77 / 1.1 = 70%
>
> Conventional bus versus PC:
> [(9.2 - 5.9) x 1.5 + (9.2 – 1.2) x 0.5] / 24 hours = (4.95 + 4.0) / 24 =
> 0.37 µg/m³ added to daily average
> Percent increase = 0.37 / 1.1 = 34%

CHANGES TO YEARLY BC EXPOSURE:

> Multiply above changes by 200 / 365, (school days per year), or 55%.
>
> Worst bus versus PC: 38% increase
> Conventional bus versus PC: 19% increase

CHANGES TO LIFETIME BC EXPOSURE:

> Assume 13 years as bused student, so multiply percentage increases by 13 years / 70 year life, or 19%.
>
> Worst bus versus PC: 7% increase
> Conventional bus versus PC: 4% increase
>
> (Results rounded to one figure to reflect high uncertainty)

SUMMARY:

SCENARIO	Change in Daily Exposure on Day of Commute (%)	Change in Yearly Exposure (%)	Change to Lifetime DPM Cancer Risk (%)
Worst Bus versus PC (year 2000)	70	38	7
Conventional diesel bus vs. PC (2000)	34	19	4

RISK CALCULATIONS:

ASSUMPTIONS:
For lifetime calculations, students would ride different buses, so conventional diesel bus versus passenger car comparison was the most appropriate.

BC concentrations were converted to DPM concentrations by multiplying by 2.04 (ARB, 1998). This assumed 64% of DPM was elemental carbon (ARB, 1999) and elemental carbon concentrations should be multiplied by 0.765 to convert to BC concentrations as measured with an aethalometer (Babich et al., 2000). Therefore, the average daily DPM exposure for Los Angeles in 2000 was 2.2 $\mu g/m^3$.

The unit risk factor for lifetime exposure to DPM was 3×10^{-4} per $\mu g/m^3$ of DPM (ARB, 1998).

CHANGES TO LIFETIME CANCER RISK DUE TO INCREASE IN DPM EXPOSURE:

Lifetime cancer risk due to DPM at current LA average DPM exposure of 2.2 $\mu g/m^3 \times 3 \times 10^{-4} (\mu g/m^3)^{-1} = 7 \times 10^{-4}$ or 700 in a million.

The cancer risk Increase from lifetime DPM increases due to riding conventional diesel buses versus PCs was a 4% increase, 3×10^{-5}, or 30 in a million.

CHANGE IN RISK OF VEHICLE CRASH FATALITY DUE TO SWITCH TO PASSENGER VEHICLES FOR COMMUTE:

Assumes an 18 mile trip, twice per day:

RISK OF BUS CRASH FATALITY:
18 miles x twice per day x 5 days per week x 40 wks per year x 12 years = 86,400 miles @ 0.06 fatalities per hundred million miles (Transportation Research Board [TRB], 2002) = 5×10^{-5} or 50 in a million.

For passenger cars, risk for same distance was 2.5×10^{-4} (TRB, 2002) or 250 in a million.

INCREASE IN CRASH FATALITY RISK:

PC risk – bus risk = $2.5 \times 10^{-4} - 5 \times 10^{-5} = 2 \times 10^{-4}$ or 200 in a million.

This difference is larger than the increase in lifetime risk of cancer, although these numbers have a range of uncertainty larger than the difference (see caveats / uncertainties).

CONCLUSION:

Crash fatality risk due to switching to passenger cars from buses for school transportation probably overshadows decreased cancer risk due to decreased exposure to DPM, but this comparison should take into account that the uncertainty of the numbers is larger than their difference.

CAVEATS / UNCERTAINTIES:

Transportation fatality numbers are nationwide and differ by region. The fatality numbers are reliable in the sense that they are based on actual fatalities, but uncertainty is high because bus fatalities are rare (~20 in nine years), giving a small sample size of events.

Unit risk factor for cancer due to DPM has greater than an order of magnitude uncertainty.

Cancer risk and vehicle crash fatality risk are not directly comparable.

Other vehicle-related pollutant exposures were not taken into account.

Particulate Matter (PM2.5)

MORBIDITY CALCULATIONS:

Changes in exposure to PM2.5 are more difficult to calculate because in-vehicle passenger car PM2.5 concentrations are not well characterized.

The School Bus Study (Fitz et al., 2003) measured PM2.5 run averages from 21 to 62 $\mu g/m^3$, compared to ambient PM2.5 concentration of 23 $\mu g/m^3$ (West Los Angeles SCAQMD station, 2001 annual arithmetic mean).

CHANGES TO ANNUAL EXPOSURE:

Using similar calculations as for DPM above, worst case daily increase in PM2.5 was: [(62 – 23) $\mu g/m^3$ x 2 hrs per day] / 24 hours = 3.3 $\mu g/m^3$

This was a worst case set of concentrations and did not take into account elevated PM2.5 inside passenger cars.

Change to annual exposure =
(200 school days/365 days per year) x 3.3 $\mu g/m^3$ = 1.8 $\mu g/m^3$

CHANGES TO ASTHMA HOSPITALIZATION RATES:

Resulting change in daily hospitalization rate due to asthma:
Δ hospitalizations = y_o x ($e^{-\beta\Delta PM}$ – 1) x population (Sheppard et al., 1999, as cited in ARB criteria document)
where:

y_o = is daily asthma hospitalization rate per person, 2.6×10^{-6}
β = coefficient based on log of relative risk observed for unit PM2.5 concentration increase = 0.0025
and ΔPM is change in daily PM2.5 concentration

Assuming ΔPM = 3.3 $\mu g/m^3$, the change in rate of daily hospitalization is 2.2×10^{-8} cases per person, or an increase of 0.8% over the baseline rate for PM2.5 = 23 $\mu g/m^3$. For Los Angeles, with approximately 4 million children (age 0-17), this is 0.9 extra hospitalizations per day, or 30 extra hospitalizations per year. For a given asthmatic child, this translates to a 50 in a million chance of hospitalization during their 13 years of school commutes.

CAVEATS:

Asthma study was conducted in Seattle, where PM composition is different than LA. For example, Seattle has much more wood smoke.

Much of the PM2.5 data were missing.

The study found CO and PM2.5 highly correlated, with similar effects from each. This indicates the possibility of PM2.5 acting as more of a surrogate for automobile emissions than diesel vehicle emissions.

CHANGES TO RATE OF LOWER RESPIRATORY SYMPTOMS:

Δ lower resp. symptoms = $-[(y_0 / \{[1- y_0]\, e^{-\beta\Delta PM} + y_0\})- y_0]$ x population (Schwarz et al., 1994, as cited in ARB criteria document)

where:

y_0 = daily lower respiratory symptom incidence per person, 0.0012. (Lower respiratory symptoms defined as reports of any two of cough, chest pain, phlegm, or wheeze, so these are not necessarily severe symptoms or illness.)

β= coefficient based on log of relative risk observed for unit PM2.5 concentration increase = 0.01823

and ΔPM is change in daily PM2.5 concentration

Assuming ΔPM = 3.3 µg/m³, the change in rate of lower respiratory symptoms was 7×10^{-5} cases per person per day, or 6% over the baseline rate for PM2.5 = 23 µg/m³. For Los Angeles, with approximately 4 million children (age 0-17), this was about 300 extra cases of symptoms per day, added to an existing 4800 cases per day. For a given child, this was about a 20% increased chance of lower respiratory symptoms during their 13 years of school commutes, or 3.4 expected occurrences rather than 2.9.

CAVEATS:

Study was conducted only in the summer months (as part of Six Cities study).

Respiratory symptoms as defined were not a very serious health outcome.

CONCLUSIONS:

Daily worst-case increases in PM2.5 exposure were estimated to be 3.3 µg/m³. This would result in a 0.8% in daily asthma hospitalizations and a 6% increase in daily rate of occurrence of lower respiratory symptoms. Under worst-case conditions, changes in asthma hospitalization rates could be considered important.

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